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Ammonia as a Replacement for Medium Sized Modular R-22 Systems

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ABSTRACT

This paper indicates how ammonia systems might be adapted to make them more suitable for use on installations which traditionally adopted CFC and HCFC refrigerants in the range 100kW – 600kW cooling capacity for warehouses, blast freezers and food factory applications. The examples draw on over twenty years of experience with low charge systems in Europe, but are specifically focussed on the American market, where a ten year phase-out program for R-22 has just started. Key parameters are explained, and barriers to implementation are identified. The way in which these barriers can be overcome is illustrated through case studies and performance data logged from operational installations.

1. INTRODUCTION

The final stages of the actions mandated by the Montreal Protocol on Substances that Deplete the Ozone Layer are now in place. Article 5 of the protocol lists countries which are granted some leeway on the phase out dates due to their economic standing. They are sometimes called "Article 5 countries", or more colloquially "developing countries". In all other nations, not listed in Article 5 and sometimes called "non-article 5 countries" the use of CFCs and HCFCs in new equipment has been prohibited. According to the Montreal Protocol timetable the prohibition on HCFCs dates from 1 January 2010, so this is a new situation for many nations, including the United States of America. In other regions however, for example Europe, local regulations were used to accelerate the phase out of CFCs and HCFCs, so that R-22 has not been permitted in new installations in Europe since 2002. This difference in phaseout timetables means that many lessons have been learned in Europe, and other regions can benefit from the experience gained.

End users have a choice: they can opt to move away from HCFCs as soon as possible so that their business has the maximum amount of time to adjust to new technology, or they can conserve cash by delaying the change until the last possible moment, but then run the risk that the overstretched engineering resource is not able to meet their urgent demands when action is ultimately required. In Europe both courses of action were followed. Those who opted for change either changed the refrigerant in their equipment to an HFC, or replaced the equipment with ammonia plant. Those who delayed until the last minute were not able to design, install and commission ammonia systems quickly enough when the supply of R-22 all but dried up and were forced to make rapid conversions to HFC blends. The European regulations would have permitted the use of recycled R-22 in existing equipment until 2015, but the flow of R-22 back from the market was virtually non-existant – estimated by one commentator to be about 3% of the demand for R-22, so the availability of refrigerant is far less than expected. In the UK the current selling price (April 2010) for recycled R-22 is approximately £20 per kg, whereas a year ago, before the ban on "virgin R-22" came into effect the price was about £4 per kg. In addition the price is changing regularly, and is only going in one direction. Demand for HFC blends suitable for retrofit in existing systems is said to have increased by a factor of 4 between December 2009 and January 2010, and, like the price of R-22, is also still rising. Some end users attempted to beat the ban by building a stock of recycled R-22 before the end of 2009, buying new refrigerant and charging it into their plant, then removing the excess and storing it. This is a very high risk strategy, because one large leak could use their entire stockpile, and one stroke of a legislator's pen could change the rules and leave them needing to dispose of a large stockpile of chemical waste.

2. KEY CONSIDERATIONS IN REPLACING R-22 SYSTEMS

This paper specifically addresses the needs of users who have medium sized facilities which are currently served by packaged, air-cooled compressor/condenser packages using R-22. A typical installation might have four or five of these units mounted on the roof of a cold store, or dispersed along the length of the loading dock canopy. Each unit is about the size of a medium-sized pick-up truck and could have a refrigeration capacity up to 200kW (60TR). The units are connected to evaporators mounted in penthouses or suspended from the cold store ceiling, and installed with copper piping. They have a simple thermostat control and are expected to operate automatically without any manual intervention. Regular maintenance may not be done, and they will only receive the attention of a service technician when they stop working and the store temperature is affected.

It is possible to replace the R-22 in these systems with a blend of HFCs and there are many case histories of successful conversions. However it is likely that system capacity may be reduced, and efficiency may be worse than the R-22 system. Operating pressures may also be a bit higher, and system leakage tends to increase on the HFC blends. With care in the conversion, for example by changing the lubricant to a polyol ester and replacing all of the synthetic rubber seals the effects of capacity, efficiency and leakage can be minimized. However it is highly likely that if the refrigerant change is rushed through without sufficient planning then performance and reliability will be adversely affected.

To achieve a successful conversion, the user should consider the following points:

- What is the current performance of the system?
- How much does it leak at the moment?
- What performance is acceptable in future?
- What rate of leakage is acceptable in future?
- What steps can be taken to minimize leaks?

The current performance should be assessed on the basis of store temperature profile, downtime as a percentage of total operating time, electrical consumption per week, refrigerant top-up per week. These parameters should have been tracked for several months before the conversion is started, so that the success or otherwise of the change can be assessed, and the true impact on the business can be estimated. Therefore even if the user intends to delay the conversion for as long as possible, the monitoring should start immediately so that when action is required it can be properly appraised.

3. ASSESSMENT OF THE POTENTIAL OF AMMONIA IN THIS APPLICATION

The measurement exercise might also provide the basis for making a business case to take action earlier, in order to deal with issues in efficiency and reliability that had previously been unchecked. There are a number of good reasons for considering a switch to ammonia as the refrigerant if the equipment is to be replaced due to poor efficiency or excessive leakage.

- It should be possible to achieve significantly higher efficiency than can be reached with R-404A or other industrial HFC blends
- The leakage of ammonia from industrial systems can be reduced to zero in normal operation due to the more rugged industrial construction required due to material compatability
- The future availability of “high global warming potential” HFCs is currently under discussion. Proposals have been tabled by the United States of America and “the Island States” (Micronesia) to introduce a “phase-down” of HFCs
- If the current range of HFCs are to be replaced with other fluorocarbons in the “low global warming potential” group then these will probably be unsaturated HFCs (“uHFCs”), also known as hydrofluoroolefins (HFOs).

Each of these considerations requires further explanation.

3.1 System efficiency

The physical properties of ammonia make it very suitable as a refrigerant. It has an exceptionally high latent heat and also a high critical temperature compared with R-22. These two properties result in a very low mass flow for a

given capacity. Low mass flow results in relatively small pipe sizes and reduced pressure drop, although the vapour swept volume is high due to the low vapour density. Further details can be found in numerous publications for example the ASHRAE Refrigeration Handbook (2010) and the International Institute of Refrigeration's "Guide to Ammonia as a Refrigerant (Pearson, 2008a). These show that in comparison with R-404A ammonia is likely to consume 30% less power for a given system application, assuming similar system design considerations (evaporator and condenser sizing, compressor efficiency, pressure drop). In air-cooled systems the difference is more pronounced due to the large difference in critical pressure: for ammonia this is 133°C whereas for R-22 it is 96°C and for R-404A it is 72°C. A more complete explanation of the reasons for the disadvantage that this brings to R-404A can be found in Pearson (2010). Clearly moving from R-22 to R-404A is a step in the wrong direction in this respect. Low critical pressure also results in a high percentage of flash gas after expansion. This can be countered by the use of an economizer in screw compressors, however for R-404A the heat exchanger would need to be five times larger than that required for ammonia, and would only bring the economized R-404A efficiency up to the same level as un-economised ammonia. (Pearson, 1999).

3.2 Refrigerant leakage

Leakage rates from commercial refrigeration systems using HFCs are approximately 18% of the refrigerant charge per annum (UNEP, 2006). The majority of this leakage, 70%, is due to major releases, estimated by Clodic in 1997 and reaffirmed in a later report by Clodic et al in 2006. Most of these major releases are due to catastrophic failure of pipe and fittings (REALZero, 2009). Traditional industrial refrigeration systems using ammonia tend not to leak as much, and significant reductions have been achieved by focusing on eliminating the smell of ammonia in order to reduce the risk of injury (Pearson, 2008b). The use of steel pipe, with welded fittings also greatly reduces the probability of a refrigerant leak.

3.3 Availability of HFCs

The European "MAC Directive" (Mobile Air-Conditioning Directive, 2006) sets a threshold of 150 for the global warming potential of refrigerants to be used in the air-conditioning of new models of car after 2011, with a complete phase out of "high GWP" fluids by 2017. A recent report from the UNEP RTOC on "low GWP alternatives" sets the definition of high GWP as greater than 1000, and low GWP as less than 300. The directive has prompted a world-wide research effort into the development of alternative fluorocarbons. Since the current market in MAC for R-134a accounts for about 50% of production it is likely that supply to other markets will also be affected by the directive, albeit indirectly. However it is not at all clear what that effect might be. There may be a glut and prices will remain low for the foreseeable future, or lack of demand might cause some production plants to be closed, leaving severe shortages and high prices. There have already been a couple of occasions where short term shortages caused by production problems at the chemical plant caused a shortage and resultant spike in prices. The phase-down of HFC production was proposed at the 20th meeting of Parties to the Montreal Protocol in Doha, 2008, and presented to the Copenhagen Summit in December 2009, but no agreement was reached. The suggestion is that production of HFCs should be regulated using the Montreal mechanisms, proven to be successful over a 20 year period, with a cap on supply at 30% of 2006. This seems laudable, but it raises the prospect of accelerated reductions and ultimately phase out, as was the case with the Montreal Protocol for CFCs. "condemned to repeat"

3.4 Suitability of uHFCs

The proposed fluorocarbon alternative for MACs is R-1234yf, a hydrofluorocarbon based on propylene (propene). The double bond in the molecule results in a very short atmospheric life, and hence the global warming potential of the fluid is "ultra-low"; less than 30, according to the UNEP RTOC classification. Extensive testing has shown good performance and stability in sealed automotive systems, and testing is now being conducted on the suitability of these compounds for chillers and commercial refrigeration. However Low (2010) has shown that acid tends to form in the presence of moisture, which suggests that they will not provide sufficient stability in larger commercial or light industrial systems of the type discussed in this paper. It is extremely unlikely that an unsaturated hydrofluorocarbon (uHFC) will have been commercialized in these markets in the next five years, but this is the timescale under discussion for the initial HFC phasedown.

The family of CFCs and HCFCs contains a broad range of fluids with atmospheric boiling points ranging from R-22 at -40°C through R-12 at -30°C and R-134a at -26°C to r-123 at 23°C and R-123 at 27°C. In general the boiling point is related to molecular weight – the heavier molecules boil at higher temperatures. The same is true for the unsaturated HFCs, but with the added twist that those based on ethylene (ethene) and butylene (butene) are highly toxic. The heavier propene based uHFCs, R-1216 and R-1225ye(Z) have also been found to be toxic, leaving the R-

1234 (tetrafluoropropene) and R-1243 (trifluoropropene) families of isomers as the only contenders. In the same way as R-12 was suitable for car air-conditioners but not for industrial refrigeration, it seems unlikely that these fluids hold much promise for the industrial sector. uHFCs could be blended with more stable (higher GWP) chemicals to produce a compromise solution, but for this to be non-flammable it is likely to have a GWP higher than 300, and so will be, at best, in the "moderate" category.

In contrast consider where ammonia fits in these four considerations. It offers better efficiency than has been seen from any of the HFCs to date. It is a proven, low leakage refrigerant. It is widely available at a relatively low price. However suitability for the heavy commercial market is a more difficult question.

Ammonia is toxic and combustible. If the new refrigerant class of A2L is introduced in ISO5149 and ASHRAE-15 as proposed (ISO, 2009) then ammonia would be class B2L. This new "2L" designation denotes products which are "mildly flammable", but difficult to ignite and which cause less damage when they burn due to the low speed of flame propagation. The A and B designation relates to toxicity, since ammonia's long term exposure limit (LTEL), the eight-hour time-weighted average, is less than 400ppm it is in category B. However the traditional toxicity classification does not take account of the products of combustion or degradation. All HFCs produce toxic products, including HF when they burn, and uHFCs as mentioned earlier are less stable than saturated HFCs. In contrast ammonia burns to N_2 and H_20: harmless and abundant in the atmosphere. It is reasonable to conclude that products of degradation should be considered more carefully if unsaturated compounds, which by definition are more likely to degrade in use, are to be used. On balance, and considering the well-known pungent odour of ammonia in contrast to the unfamiliar and reportedly not unpleasant smell of highly toxic hydrofluoric acid, it seems that the toxicity risk associated with ammonia use are significantly easier to manage than the alternatives.

Traditional ammonia systems used in industrial cold storage and freezing however are not readily adapted to the heavy commercial/light industrial sector more used to packaged R-22. A traditional ammonia plant would be two stage compression, pumped circulated with evaporative condensers and a charge of several tonnes and with all the compression and pumping equipment housed in a purpose built special machinery room. This would not be an easy retrofit in an existing medium-sized facility which did not have a special machinery room and had no previous experience of maintaining a large ammonia facility. In addition, if the system charge exceeded 10,000 pounds (4,546kg) then, in the USA, the plant would need to be registered under the rules laid down by the Occupational Safety and Health Administration (OSHA). These mandate a range of compulsory measures including registration with local authorities, periodic inspection, strict requirements on reporting of any emissions and preparation of an offsite consequence analysis and emergency response plan (including regular drills).

There is a clear imperative to keep the charge of each system below the 10,000 pound threshold. This can be done through a number of strategies:

- Split the plant into separate modules with no cross connection
- Avoid "low pressure float" control, which requires a reservoir of liquid on the high pressure side
- Avoid thermosyphon oil cooling for the same reason
- Avoid two stage compression which requires intercooling
- Use DX economizers to improve the performance of single stage plant without raising the charge
- Avoid hot gas defrost, which requires a large receiver to collect the condensate generated during defrost
- Avoid long liquid lines – locate the condensers close to the evaporators

These can all be achieved through the use of a system described by S Forbes Pearson in a paper to the Institute of Refrigeration in 1996. A flow diagram of this type of system is shown in Figure 1. The compressor, condenser and evaporator are much the same as would be found in any other ammonia system, but some of the other components require some further explanation. The liquid flowing from the condenser to the expansion valve is subcooled by exchanging heat with liquid in the receiver. This ensures that the suction gas drawn to the compressor is dry, even though the return from the evaporator is wet. The expansion valve is placed after the subcooler, but is controlled by a float switch at the condenser. The control is arranged to open the valve if there is liquid at the condenser outlet, so there is no prospect of holding a reservoir of liquid on the high pressure side of the system. The discharge gas from the compressor and the suction gas from the evaporator pass through a four port ball valve. To defrost the evaporator the ball is turned 90 degrees and the system runs as a heat pump for a short period. This gives a quick and efficient defrost with no risk of liquid hammer or hydraulic shock. It also eliminates the possibility of

inefficient hot gas leakage during normal operation. The check valve in parallel with the expansion valve is to provide a bypass during reverse cycle operation. It is sometimes necessary to fit a second expansion valve (with non-return valve) on the condenser side of the subcooler to provide expansion during defrost operation. There is a pot on the bottom of the subcooler for collecting oil. This can be drained manually or, as shown in the diagram, it can be filtered and returned automatically to the compressor suction.

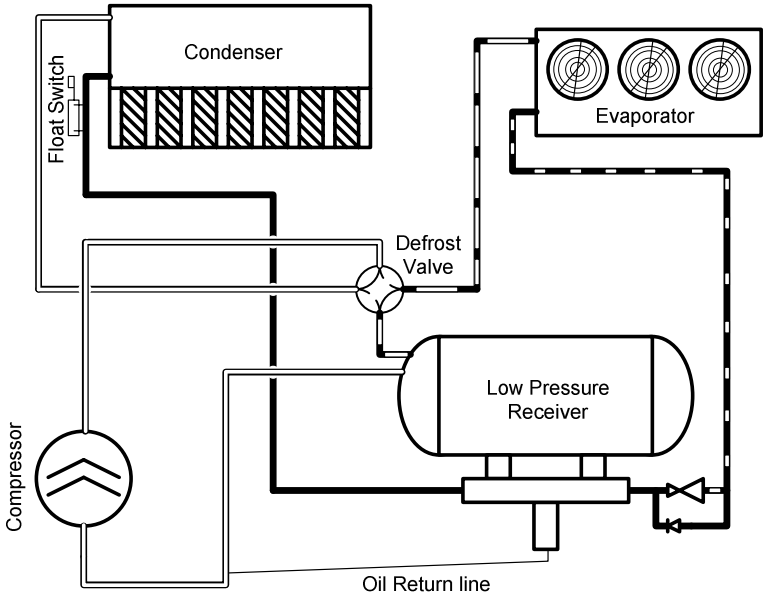

Figure 1 – Simplified flow diagram for an ammonia low pressure receiver system

The system is a form of direct expansion, since the liquid and gas from the expansion valve go "directly" to the evaporator (ie without being recirculated through a pump loop), but unlike conventional DX systems the suction from the evaporator is wet, so the full evaporator surface is used, and there is no superheat penalty on suction pressure. Like other DX systems the distribution of liquid and gas within the evaporator is critical: this means that some restrictions must be placed on the size, number and orientation of the air coolers. Up to four evaporators can be served by a simple system provided the liquid line is correctly balanced and distributors are used at each evaporator. The system is therefore best suited to smaller cold stores or installations where the plant can be arranged in modules serving groups of coolers. It is particularly well suited to penthouse applications where a packaged compressor set can be located on the roof next to the penthouse. The largest cold store evaporator that can be served by this type of system is about 250kW (75TR), and the optimum size is about half this. So a system with four coolers could provide 1000kW of cooling in a storage or freezing system.

4. CURRENT STATUS

Ammonia low pressure receiver systems have been installed in the United Kingdom since the late 1980s and have been used for cold storage, blast freezers, spiral freezers, chill stores, and in conjunction with plate heat exchangers for liquid chillers. Earlier installations used galvanized steel or stainless steel coolers, but in both cases it was difficult to achieve good distribution within the coolers under all load conditions. Recent developments in aluminum evaporators have significantly improved the boiling heat transfer within the cooler, and the better coefficient of heat transfer through the tube wall has ensured that the finned surface of the cooler is more effectively utilized. At a test site in Harlow, England a pair of stainless steel coolers installed with the original installation in 2002 were replaced with aluminum coolers in March 2009. Plant data logged between March and October suggest that the daily power consumption of the plant dropped from 1000kWh per day to 800kWh per day. This is attributed to the higher suction pressure and consequent improved CoP and reduced running hours achieved. A second installation is currently under construction, replacing R-22 plant in an installation completed in 1979. This system will be commissioned in June 2010, so more information will be available at the conference. The four evaporators are served by a single receiver and a pair of ammonia compressors. The plant has a capacity of 300kW.

5. FUTURE POTENTIAL

For systems in the medium sized R-22 sector it is possible to combine the benefits of the low pressure receiver with a packaged air-cooled compressor/condenser set. This arrangement is described in the context of water chillers by Pearson (2010). The arrangement of the condenser around the compressors, electrical panel and low pressure receiver is shown in Figure 2.

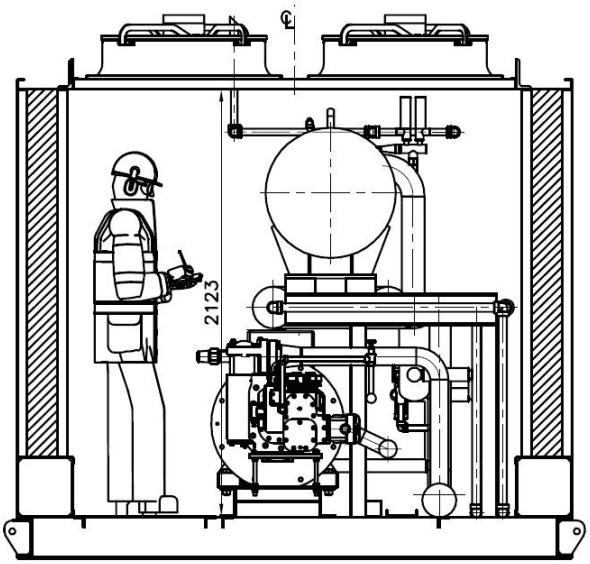

Figure 2 – arrangement of equipment in a packaged engineroom formed from an air-cooled condenser

The only differences between the air cooled chiller and the LPR system are that the plate and frame heat exchanger for the water cooling evaporator is not fitted, and a four port ball valve for defrost is added. The condenser is constructed from stainless steel tubes with coated aluminum fins. If the unit is to be installed in a noise sensitive area then housings can be provided for the screw compressors and slower running fans can be fitted to the condenser. It is also possible to fit adiabatic pads to the condenser faces to provide some pre-cooling of the air supply to the condenser. These pads are only used when the dry bulb temperature is high and there is a significant wet bulb depression.

The standard package configuration, with two screw compressors, gives up to 240kW (70TR) at cold storage conditions, and up to 780kW (220TR) at chill conditions. This sizing fits very well with the modular approach favoured in the medium sized cold stores where a pair of evaporators in a penthouse serve one bay of the store and are fed by a rooftop mounted condensing unit.

6. CONCLUSIONS

The excellent thermodynamic properties of ammonia set it apart from the recently developed HFC and uHFC refrigerants, which are likely to require 30% - 50% more electrical consumption for the same job. The dual safety concerns of toxicity and flammability can be fully addressed by designing the ammonia system for low charge and locating the equipment outdoors close to the evaporators. The low charge also means that the system is not subject to the complex management regulations which apply to larger ammonia systems.

The low pressure receiver system, which has been used with ammonia in Europe for twenty years offers an alternative to end users who are required to get rid of existing R-22 plant, but do not want to switch to traditional pumped ammonia systems and are concerned about the long term availability of HFCs or uHFCs. The capital cost of the ammonia pack is higher than a R-404A unit would be, mainly due to the rugged industrial construction and longer life expectancy. The efficiency is also higher than the R-404A system so it is possible to construct a payback on a case-by-case basis. When the cost of a special machinery room, required for a traditional ammonia installation, is factored out of the total project cost, the packaged LPR is a very attractive option. Operator costs are also lower

than required for pumped ammonia systems as the packs are fully automatic, only requiring periodic maintenance as specified by the compressor and condenser manufacturers.

This gives a credible “natural” alternative for R-22 replacement.

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